

The birth rate of SNe Ia from hybrid CONe white dwarfs

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ABSTRACT

Considering the uncertainties of the C-burning rate (CBR) and the treatment of convective boundaries, Chen et al. (2014) found that there is a regime where it is possible to form hybrid CONe white dwarfs (WDs), i.e. ONe WDs with carbon-rich cores. As these hybrid WDs can be as massive as $1.30 M_{\odot}$, not much mass needs to be accreted for these objects to reach the Chandrasekhar limit and to explode as Type Ia supernovae (SNe Ia). We have investigated their contribution to the overall SN Ia birth rate and found that such SNe Ia tend to be relatively young with typical time delays between 0.1 and 1 Gyr, where some may be as young as 30 Myr. SNe Ia from hybrid CONe WDs may contribute several percent to all SNe Ia, depending on the common-envelope ejection efficiency and the CBR. We suggest that these SNe Ia may produce part of the 2002cx-like SN Ia class.

Subject headings: supernovae: general - star: white dwarfs

1. INTRODUCTION

As very good cosmological distance indicators, Type Ia supernovae (SNe Ia) have been successfully used for determining basic cosmological parameters; this has led to the discovery of an accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). However, the exact nature of SNe Ia is still not clear, especially concerning their progenitor systems (Hillebrandt & Niemeyer 2000; Leibundgut 2000); indeed, the identification of their progenitors is important for several astrophysical fields (Wang & Han 2012). It is for about four decades that two basic scenarios for the progenitor of SNe Ia have been competing. In the single-degenerate (SD) model, a carbon-oxygen white dwarf (CO WD) grows in mass

via accretion from a non-degenerate companion (Whelan & Iben 1973; Nomoto et al. 1984) while, in the double-degenerate (DD) scenario, two WDs merge after losing orbital angular momentum by gravitational wave radiation (Iben & Tutukov 1984; Webbink 1984). At present, there is some observational and/or theoretical support for both basic scenarios, but there are also counter-arguments (e.g., Maoz, Mannucci & Nelemans 2014; Ruiz-Lapuente 2014).

The discovery of circumstellar material from the SN Ia progenitor system has provided significant evidence in support of the SD scenario (Patat et al. 2007; Sternberg et al. 2011; Dilday et al. 2012), but a major shortcoming of the model is that present estimates of their birth rate appear to be somewhat lower than the observationally inferred rate (Han & Podsiadlowski

2004; Meng & Yang 2010; also see Hachisu et al. 1999a; Yungelson & Livio 2000; Ruiter et al. 2009; Mennekens et al. 2010; Claeys et al. 2014). One reason for the low birth rate is that it is difficult to increase the WD mass to reach the Chandrasekhar limit (Branch et al. 1995; Howell 2001; Maoz & Mannucci 2012; Maoz, Mannucci & Nelemans 2014;). Recently, following the discovery of Denissenkov et al. (2013), Chen et al. (2014) found that considering the uncertainty of the C-burning rate (CBR) and the treatment of convective boundaries, hybrid CONe WDs with a carbon-rich core may form instead of pure ONe WDs even for stars with an initial mass larger than $7.0 M_{\odot}$. In their most extreme case (for a CBR efficiency factor of 0.1), the hybrid WD could be as large as $1.30 M_{\odot}$. It is relatively easy for such WDs to accrete enough mass to reach the Chandrasekhar limit, i.e. the discovery by Chen et al. (2014) could increase the fraction of stars that form WDs capable of igniting carbon in a thermonuclear runaway and contribute to the birth rate of SNe Ia. Chen et al. (2014) did not yet estimate the birth rate of SNe Ia from hybrid CONe WDs. The purpose of this paper is to provide such estimates using binary population synthesis (BPS) based on the results in Chen et al. (2014).

In Section 2, we describe our method and present the results of our calculations in Section 3. In Section 4, we conclude with a short discussion of the implications.

2. METHOD

To estimate the birth rate of SNe Ia from hybrid CONe WDs, we do not new binary evolution calculations but can use previously published ones. Based on the optically thick wind model (Hachisu et al. 1996), Meng et al. (2009) already obtained a dense model grid leading to SNe Ia with different metallicities and initial WD masses. In their calculations, they only considered the case of main sequence or sub-giant companions (WD + MS). Here, we also only consider the WD + MS case since the contribution to the total SNe Ia from WD binaries with red-giant companions is quite uncertain (e.g. Yungelson et al. 1995; Hachisu et al. 1999b; Han & Podsiadlowski 2004). Using the results of Meng et al. (2009), we simply extrapolate the WD mass by a linear assumption

to obtain the parameter space leading to SNe Ia for $M_{\text{WD}}^i = 1.30 M_{\odot}$. Fig. 1 shows the contours leading to SNe Ia for different initial WD masses.

To obtain the birth rate from hybrid CONe WDs, we carried out a series of detailed Monte Carlo simulations with the rapid binary evolution code developed by Hurley et al. (2000, 2002). We assumed that, if a WD is less massive than the most massive hybrid one shown in Fig. 5 of Chen et al. (2014) and is not a CO WD, it is a hybrid CONe WD. If a binary system in the simulations evolves to the CONe WD + MS stage and the system is located in the $(\log P^i - M_2^i)$ plane for a SN Ia at the onset of Roche-lobe overflow (RLOF), we assume that carbon may be ignited in the center of the WD no matter how massive the CO core is in the hybrid WD, and then a SN Ia is produced. We follow the evolution of 10^8 sample binaries. This evolutionary channel is described in more detail in Meng et al. (2009). As in Meng et al. (2009), we adopted the following input for the simulations: (1) A single starburst (where $10^{11} M_{\odot}$ of stars are formed at the same instant of time) or a constant star formation rate over the last 15 Gyr. (2) The initial mass function (IMF) of Miller & Scalo (1979). (3) A constant mass-ratio distribution is taken to be constant. (4) The distribution of separations in $\log a$ for wide binaries, where a is the orbital separation. (5) Circular orbit for all binaries. (6) The common envelope (CE) ejection efficiency α_{CE} , which denotes the fraction of the released orbital energy used to eject the CE, is set to 0.5, 0.75, 1.0 or 3.0. (See Meng et al. (2009) for details). In this paper, we do not test the effect of other inputs to produce the binary samples on the final results such as different IMF, since they may not change the basic conclusion significantly (see also Wang et al. 2013).

3. RESULTS

The birth rate of SNe Ia for a single starburst from our BPS simulations is presented in Fig. 2. It shows that most supernovae occur between 0.1 and 1 Gyr after a starburst, even though some SNe Ia can be as young as 30 Myr. The contribution of these extremely young SNe Ia decreases with decreasing α_{CE} . These extremely young SNe Ia come from the He star channel, as defined in

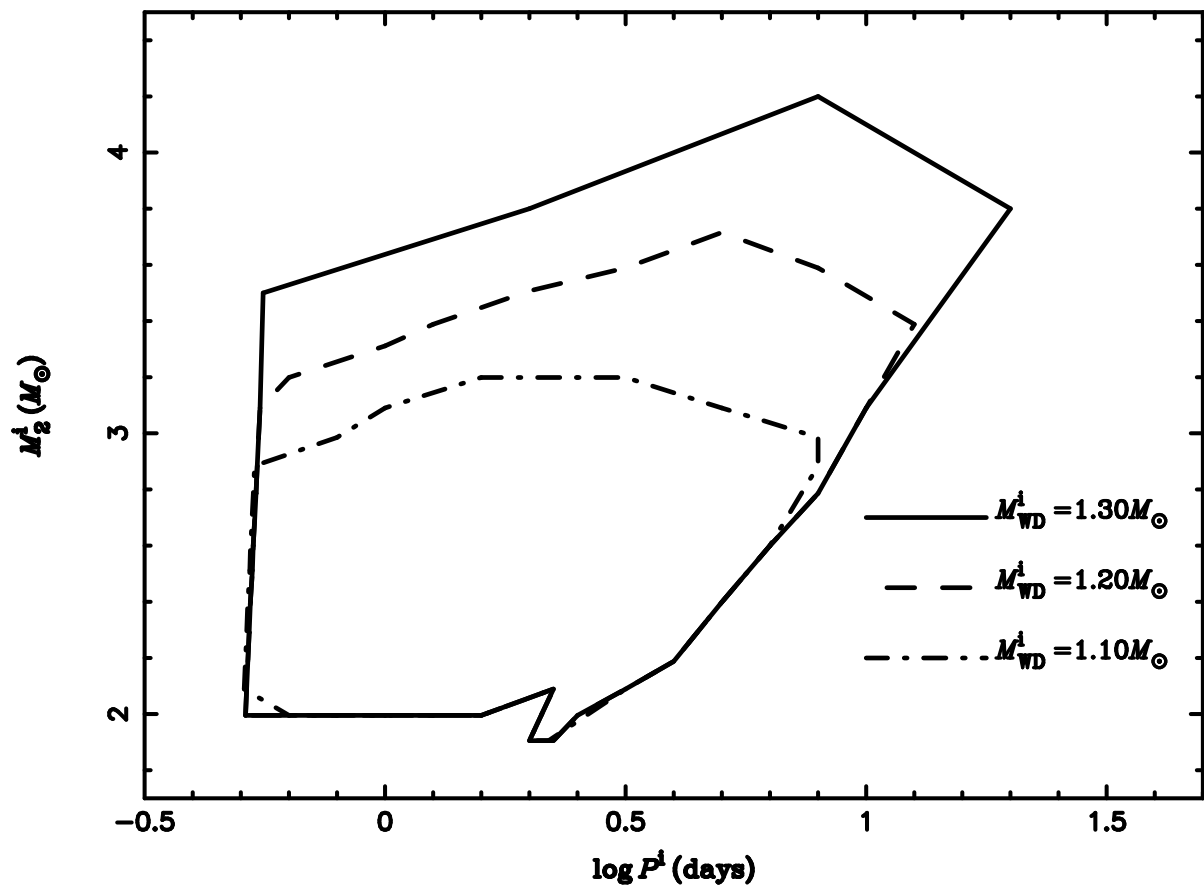


Fig. 1.— Contours in the orbital period – secondary mass plane for WD binaries leading to SNe Ia for different initial WD masses (as indicated).

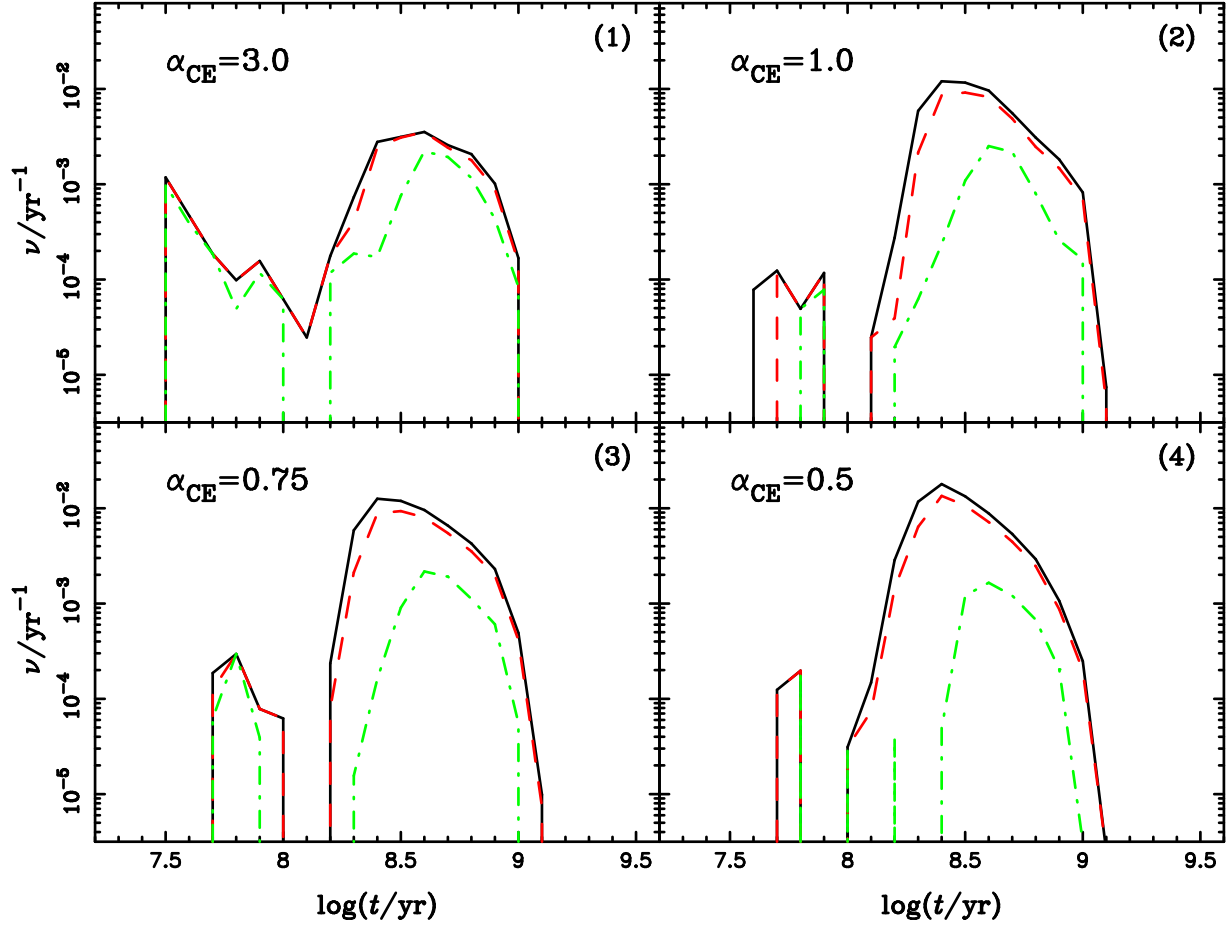


Fig. 2.— The evolution of the birth rate of SNe Ia from hybrid CONe WDs for a single starburst of $10^{11} M_{\odot}$ for different values of α_{CE} (as indicated in each panel). The solid, dashed and dot-dashed curves represent the cases for CBR factors of 0.1, 1 and 10 based on the Fig. 5 in Chen et al. (2014), respectively.

Meng et al. (2009), where the first mass-transfer phase in the primordial binary occurs when the original primary crosses the Hertzsprung gap (HG) or is on the red-giant branch (RGB). In this case, mass transfer leads to the formation of a common envelope, and the primary becomes a He star after its ejection. The helium star fills its Roche lobe again after central helium is exhausted (so-called case BB mass transfer). Since the mass donor is much less massive than before, the second phase of RLOF is dynamically stable, resulting in a close WD+MS system where the companion is helium-rich. In this binary channel, even a star as massive as $8 - 10 M_{\odot}$ can avoid the fate of a core-collapse supernova and form a WD. However, this channel is different from the one described in Chen et al. (2014), and it is still unclear whether the WD from such channel is a hybrid CONe WD or not. Irrespectively, SNe Ia from this channel are rare (see also Fig. 3).

Fig. 2 also shows that a low α_{CE} leads to a higher birth rate (see also Fig. 3) since, for a low α_{CE} , the primordial system needs to release more orbital energy to eject the CE to form a WD + MS system; this produces WD + MS systems that tend to have shorter orbital periods which more easily fulfill the condition for SNe Ia. At the same time, more and more systems which could otherwise pass through the He star channel merge with decreasing α_{CE} ; this results in a decrease of the number of SNe Ia from this channel. Fig. 2 also shows that the birth rate decreases with the CBR factor, but the difference between a CBR factor of 0.1 and 1 is not significant as the very massive WDs are rare.

Fig. 3 shows the Galactic birth rates of SNe Ia for a constant star formation rate (SFR = $5.0 M_{\odot}/\text{yr}$) from hybrid CONe WD. The Galactic birth rate is around $0.26 - 2.4 \times 10^{-4} \text{yr}^{-1}$, depending on α_{CE} and the CBR factor. This is much lower than that inferred overall SN Ia rate from observations ($3 - 4 \times 10^{-3} \text{yr}^{-1}$, van den Bergh & Tammann 1991; Cappellaro & Turatto 1997). Hence these can only contribute between 0.65% and 8% of the total SN Ia rate. Again, the Galactic birth rate increases in line with an decreasing CBR factor and α_{CE} .

Fig. 4 shows the mass distribution of the initial masses of the hybrid CONe WDs. Most of the WDs are initially more massive than $1.05 M_{\odot}$ (the

upper limit for CO WDs in Fig. 5 of Chen et al. (2014) for a CBR factor of 1, see also Meng et al. (2008)); i.e. irrespective of the correct value of α_{CE} , most SNe Ia come from the channel described by Chen et al. (2014), and the contribution from the He star channel is only minor. There is a relatively small difference of distribution between CBR factors of 0.1 and 1, as well as the birth rate as shown in Figs. 2 and 3.

4. DISCUSSIONS AND CONCLUSIONS

4.1. Uncertainties

In this paper, we examined the evolution of the birth rate of SNe Ia from hybrid CONe WDs, proposed by Chen et al. (2014), and found that such SNe Ia could potentially contribute between roughly 1 and 8% of the overall SN Ia rate. The two main uncertainties are the CBR factor and α_{CE} . All of these estimates are based on an assumption that, if a WD is less massive than the most massive hybrid one shown in Fig. 5 of Chen et al. (2014) and is not CO WD, it is a hybrid CONe WD; however, the boundary between the CO WD and the hybrid CONe WDs here is based on a CBR factor of 1 in the Hurley code, and even for the CBR factor of 1, the mass limit of initial main sequence stars for carbon ignition in Chen et al. (2014) is slightly higher than that in the Hurley code for a relatively smaller convective overshooting in Chen et al. (2014). So it is possible that, for a CBR factor of 0.1 and 1, we could overestimate the birth rate of SNe Ia while, for a CBR factor of 10, we could underestimate it. The results presented here also include SNe Ia from the He star channel, which is different from the suggestion by Chen et al. (2014). At present, it is unclear whether this channel can produce hybrid CONe WDs. Fortunately, the contribution for hybrid CONe WDs from the He star channel is small, i.e. those with an initial mass less than $1.05 M_{\odot}$ (see Figs 3 and 4); therefore the effect of these uncertainties on our final results is not significant. In addition, we only considered the case of WD+MS channel, but a WD of $1.30 M_{\odot}$ could also reach the Chandrasekhar limit by wind or normal Roche lobe overflow for a RG donor. At present, the fraction of SNe Ia from the RG channel is very uncertain, but believed to be small (Yungelson et al. 1995; Han & Podsiadlowski 2004; Ruiter et al.

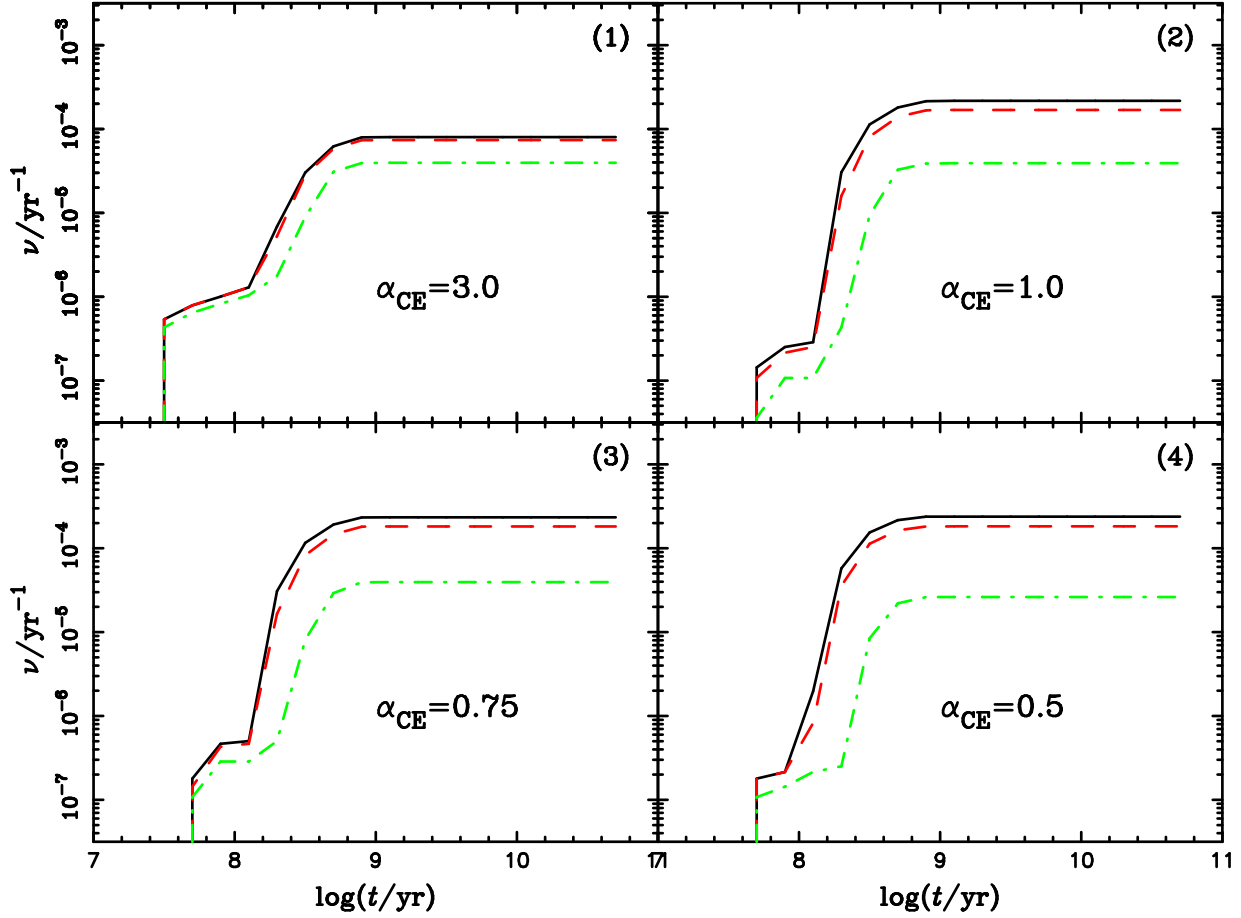


Fig. 3.— The evolution of the birth rates of SNe Ia from the hybrid CONe WDs for a constant star formation rate for different values of α_{CE} (as indicated in each panel). The solid, dashed and dot-dashed curves represent the cases for CBR factors of 0.1, 1 and 10 based on the Fig. 5 in Chen et al. (2014), respectively.

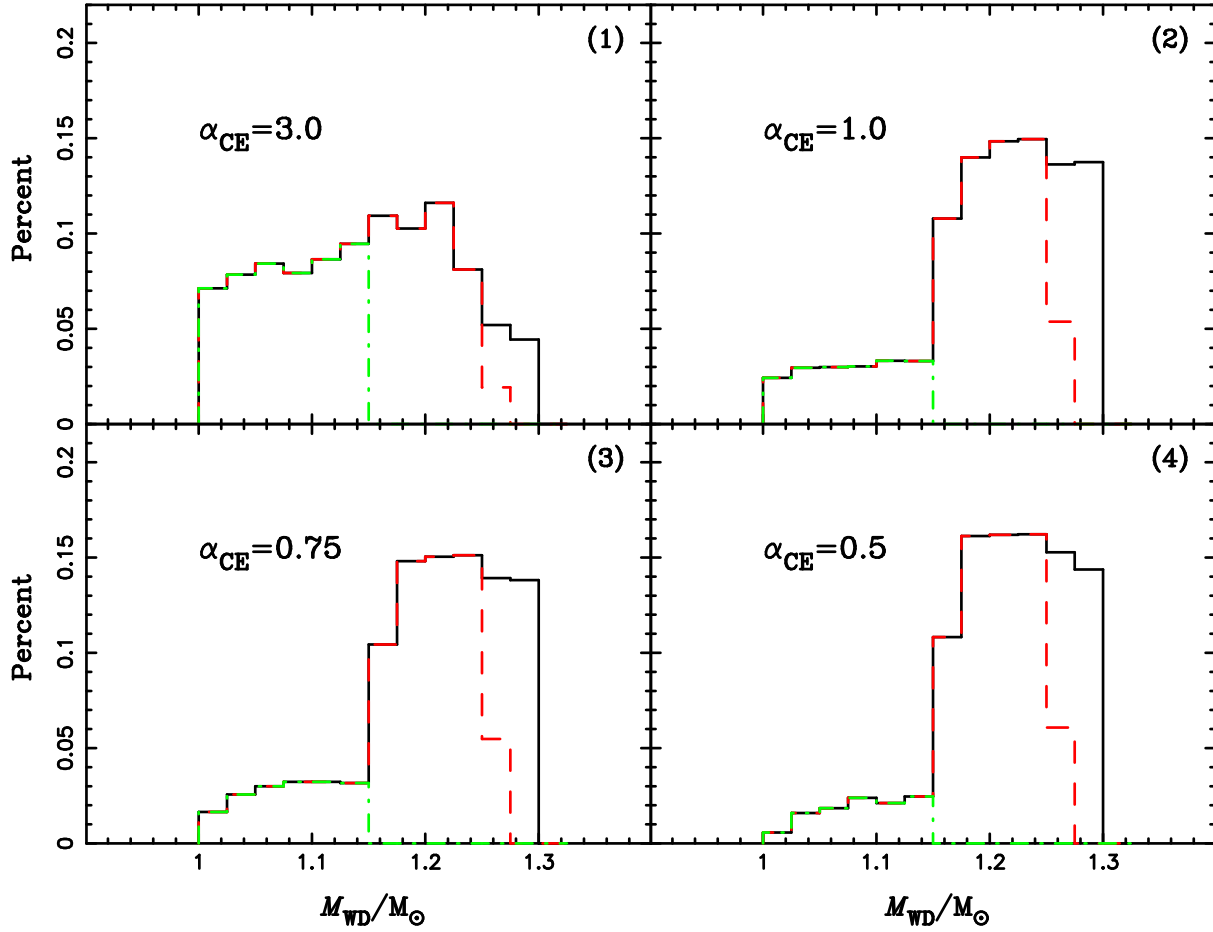


Fig. 4.— The distribution of the initial hybrid CONe WD masses for different values of α_{CE} . The solid, dashed and dot-dashed histograms represent the cases for CBR factors of 0.1, 1 and 10 based on the Fig. 5 in Chen et al. (2014), respectively.

2009; Meng & Yang 2010; Wang, Li & Han 2010; Mennekens et al. 2010); and therefore this channel probably does not significantly add to our estimates of the SN Ia rate with CONe WDs. Moreover, although we assumed that all the hybrid WDs may produce SNe Ia, it is indeed unclear what is the smallest C-core mass to make thermonuclear ignition at present. If there is such smallest C-core mass, the birth rate of SNe Ia from the hybrid CONe WDs in this paper should be taken as an upper limit. Furthermore, CE is very important for the formation of WD + MS system (see Meng et al. 2009), while whether a CE forms or not depends on the comparison of a donor star's radial response to mass loss with the response of its Roche radius. Recently, the response of fully convective giants to rapid mass loss has been severely questioned (Woods & Ivanova 2011; Passy et al. 2012), which means that it becomes relatively difficult to form a CE, and then relatively difficult for a WD + MS system to fulfill the condition leading to SNe Ia. So, according to the discussions above, we conclude that a conservative upper limit for the contribution to all SNe Ia from the hybrid CONe WDs is about 10 %.

4.2. The effect of the CBR factor

One of the motivations in Chen et al. (2014) comes from the uncertainty of the carbon burning rate. Here, we only explored three values for the CBR factor. However, based on the WD mass distribution in Fig. 4 and the relation between hybrid WD mass and the CRB factor in Fig. 5 of Chen et al. (2014), if the CRB factor is larger than ~ 400 , hybrid CONe WDs could **not** contribute to the SN Ia rate. Whatever, the contribution to all SNe Ia from the hybrid CONe WDs decreases with increasing CRB factor. In addition, from Fig. 5 of Chen et al. (2014), one may expect that if the CRB factor were as large as 100 or 1000, the birth rate of SNe Ia from the SD model should be much smaller than the present estimations.

4.3. The properties of SNe Ia from hybrid CONe WDs

The present study shows that SNe Ia from hybrid CONe WDs are relatively young and could be as young as 30 Myr. Such SNe Ia may follow the star formation in late-type galaxies. In addition, compared with normal CO WDs, hybrid CONe

WDs have a relatively low carbon abundance. If the maximum luminosity of SNe Ia is determined by the carbon abundance, i.e. a low carbon abundance leads to a dimmer SN Ia (Nomoto et al. 2003), SNe Ia from hybrid CONe WDs should have a lower peak luminosity. Moreover, for the same reason, a low explosion energy could be expected, i.e. such SNe Ia have a relatively low kinetic energy per unit mass. Finally, for SNe Ia from the He star channel, the accreted material by the hybrid CONe WDs is helium-rich, which could lead to the detection of helium lines in early spectra of such SNe Ia.

4.4. A possible progenitor for 2002cx-like supernova?

2002cx-like SNe Ia (referred to as Type Iax supernovae by Foley et al. 2013) are excellent candidates for observational counterparts of SNe Ia from CONe WDs. They exhibit iron-rich spectra at early phases like SN 1991T, while the luminosity may be as low as that of the faint SN 1991bg and the expansion velocity is roughly half of those of normal SNe Ia (Li et al. 2003). A few such events show helium lines in their spectra (Foley et al. 2013). Furthermore, 2002cx-like SNe Ia favour late-type galaxies. Their contribution to the overall SN Ia rate is quite uncertain due to the heterogeneity of this subclass (Narayan 2011): estimates of their fractional contribution range from $5.7^{+5.5}_{-3.8}$ (Li et al. 2011) to 31^{+17}_{-13} % (Foley et al. 2013). One of the main causes for these differences arises from the uncertainty whether very sub-luminous SNe like SN 2008ha should be included in the group or not. The above properties of 2002cx-like SNe Ia are quite similar to those from hybrid CONe WDs. Considering the uncertainty of the fraction for SN 2002cx-like objects and taking into account that at least one 2002cx-like event (SN 2008ge) is hosted by a S0 galaxy with no signs of star formation, we suggest that SNe Ia from the hybrid CONe WDs might explain part of the SN 2002cx-like population. Another part could be from double detonation explosions where a CO WD accretes helium-rich material from a helium star (Wang et al. 2013) and some could actually be due to fall back in a core-collapse supernova (Moriya et al. 2010). Irrespective of these uncertainties, we encourage numerical simulations of thermonuclear explosions of hybrid

CONE WDs to further explore our suggestion.

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